RESEARCH MEMORANDUM

LEADING-EDGE CONTOURS FOR THIN SWEPT WINGS: AN ANALYSIS OF LOW- AND HIGH-SPEED DATA

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NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

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SUMMARY

Important aspects of current data on thin swept wings with "bulbous" leading-edge contours (defined herein) are reviewed and analyzed.

It is found that outboard concentration of a bulbous contour will generally yield most or all of the characteristic low-speed benefit attainable from the use of such a contour. In a wing with appreciable taper, such outboard concentration may not result in any significant wave-drag penalty.

Despite the limited nature of the high-speed data reviewed, it is suggested that a combination of appropriate spanwise variation of leading-edge contour with favorable-interference design might not yield any wave-drag penalty due to bulbousness, at least at the design speed.

INTRODUCTION

Certain aerodynamic characteristics of thin swept wings are often critically dependent on leading-edge contour. This is particularly true at the two extremes of flight speed, the very low and the very high.

At low speeds, the problem is one of maintaining attached flow around the leading edge to high lift coefficients. The problem arises not only for simple wings, but for any high-lift configurations where leading-edge flow separation limits the lift or stability otherwise attainable. Such leading-edge flow separation may, for example, limit the effectiveness of boundary-layer control applied to flaps.

Within the limitations of given thickness ratio and camber, the type of leading-edge contour known to yield improved flow control, as compared with that attainable from conventional contours (such as those of the NACA

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six-series and four-digit series airfoil sections), consists of a relatively large leading-edge radius combined with smooth continuity of curvature on the upper surface. Such a contour will result in a general thickening of the forward portion of the airfoil. For convenience (and in a purely relative sense), this type of contour will be termed "bulbous."

While the bulbous leading edge affords a powerful geometric solution to the low-speed problem (within the limitations mentioned), it is the source of the high-speed problem: at speeds for which the leading edge is "supersonic" (sweep of the Mach cone exceeding the leading-edge sweep), a serious wave-drag penalty is likely.

Two design principles appear as likely means of retaining most or all of the low-speed benefit of a bulbous leading edge, while minimizing the expectation of a wave-drag penalty. First, the bulbous contour can be concentrated in the outboard region of the swept wing, where initial low-speed flow separation normally occurs, but where (if the wing has appreciable taper) only a small part of the total wing volume is located. Second, the familiar area rule can be applied, as well as other favorable-interference theories, and should result in substantial wave-drag reductions, perhaps overshadowing any penalty due to the bulbous contour.

The purpose of this report is to review and analyze important aspects of current data on thin swept wings with bulbous leading edges. Material relevant to both the above design principles is included. Because the data are far from comprehensive, areas of future research are suggested.

NOTATION

$\frac{b}{2}$	wing semispan
c'	chord of wing section lying normal to its own quarter-chord line
C_D	drag coefficient
C_{D_o}	drag coefficient at zero lift
$C_{D(o)}$	drag coefficient near zero lift
ΔC_{D_o}	rise of C_{D_o} above subsonic level
$\Delta C_{D(o)}$	rise of $C_{D(o)}$ above subsonic level
C_L	lift coefficient
$C_{L_{max}}$	maximum lift coefficient

C_m pitching-moment coefficient

M Mach number

R Reynolds number

α angle of attack, deg

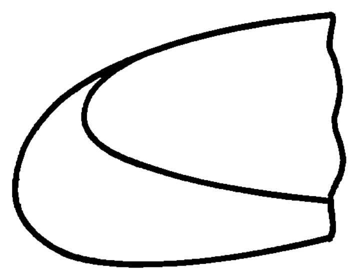
η fraction of wing semispan

REVIEW AND DISCUSSION OF EXISTING DATA

For convenient reference, the material reviewed herein is summarized in table I. The material was obtained from references 1 to 9, and from table II and the Appendix of this report.

Wherever leading-edge contours are illustrated, they apply to wing sections lying normal to their own quarter-chord line.

While for optimum comparison of bulbous and conventional contours there should be no difference in camber between them, a small difference does exist for some of the comparisons herein. Such camber is likely to be introduced, for simplicity of construction, when a bulbous contour is designed as a modification to some existing wing, as indicated in sketch (a).



Sketch (a)

Presented in the Appendix are some previously unpublished data, which are drawn upon in the main text and figures.

Data at Low Speeds

Wings with constant leading-edge contour.- Typical polars are presented in figure 1 for wings of two plan forms. Polars were selected as the most sensitive indication from longitudinal data of the onset and severity of flow separation with increasing lift.

The marked superiority of the bulbous-contour wings, as against the conventional-contour wings, is immediately evident. Since this is entirely to be expected on the basis of two-dimensional data (refs. 3 and 10), it will not be discussed in detail here. For a quantitative discussion, see reference 3.

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Wings with spanwise variation of leading-edge contour.- As noted in the Introduction, it should be possible to concentrate the bulbous leading-edge contour of a thin swept wing in the outboard region, and still realize most or all of the low-speed benefit attainable from full-span use of the contour. To verify this, a brief wind-tunnel investigation was undertaken with the wing of plan form B. Beginning with a constant, bulbous leading-edge section in the wing (the symmetrical section illustrated in fig. 1), the inboard forward region of the wing was progressively thinned in two stages, designated "cuts 1" and "2," respectively. The thinning did not reduce the maximum-thickness ratio of any section. To investigate extreme inboard thinning, a sharp leading-edge fairing at the body juncture was also tested, in conjunction with cut 1.

Comparative polars are presented in figure 2, as well as sketches illustrating the extent and degree of the cuts, and the resulting spanwise variations of leading-edge radius. The data curves indicate no adverse effect of cut 1, and only a slight deleterious effect of cut 2. Further, while the sharp leading-edge fairing at the body juncture caused a more serious deterioration of the characteristics, the wing with the fairing was still definitely superior to the wing with a constant, conventional contour.

The effect of a more drastic, full-span variation of contour in the same wing is shown in figure 3. The characteristics are seen to be inferior to those of the part-span cut contours, but superior to those of the conventional contour wing. This is consistent with the trend of the data in thinning the wing from cut 1 to cut 2, and serves to illustrate the need for an adequately bulbous contour over a sufficiently extensive outboard region of the wing.

High-lift configurations with spanwise variation of leading-edge contour.- Presented in figure 4 are the effects on drag and pitching moment of a part-span bulbous leading edge on an airplane model with leading- and trailing-edge flaps, which were deflected as indicated. Area-suction boundary-layer control was applied to the knees of both flaps, except for the farthest inboard segment of the leading-edge flap. The effect of the bulbous contour is striking: not only was there a large increment in $C_{L_{max}}$, but substantially attached flow to near $C_{L_{max}}$ may be inferred from the curves. Pressure distributions showed that the earlier stall of the conventional-contour wing was clearly due to leading-edge flow separation.

In figure 5 is shown the effect on $C_{L_{max}}$ of the outboard extent of the bulbous contour of figure 4. (The data are for a flap configuration the same as that of figure 4, except for the point corresponding to a full-span bulbous leading edge: for that point only, the break between the 30° and 50° segments of the leading-edge flap was farther outboard by 0.1 b/2.) The figure clearly shows the primary need for the bulbous contour in the outboard region of the wing, despite the high inboard loading.

Many flap and bulbous-contour configurations of this model were tested. The flap configuration illustrated was one of the most effective. It seems quite significant that a configuration such as this, combining high inboard loading, large deflection of the leading edge outboard, and protection of the flap hinge lines by artificial means, still left a leading-edge flow separation problem, and that the problem was so markedly alleviated by a simple contour change to the outboard leading edge.

It is concluded that, for many applications, outboard concentration of a bulbous leading-edge contour will indeed yield most or all of the low-speed benefit attainable from the use of such a contour.

Data at High Speeds

Wings with constant leading-edge contour.- The effect of bulbous leading edges on the zero-lift wave drag of thin swept wings is indicated by the data of figure 6. While the data are from several sources, and were obtained by various techniques, comparative curves for each plan form were obtained in identical ways, and therefore constitute a valid indication of the effect of bulbous leading edges. For each plan form, the Mach number for a sonic leading edge, that is, the Mach number for which the component of free-stream velocity normal to the leading edge is sonic, is indicated. (The sections of each of the wings of plan form E were not actually constant, but varied from streamwise NACA 0003-X3 sections at the root to streamwise NACA 0006-X3 sections near the tip; however, the wings are considered here since relative contour differences among the wings were the same at any span station.)

The data show little effect of bulbous contours on zero-lift drag at speeds well below sonic-leading-edge speed. As the sweep of the Mach cone exceeds that of the leading edge, however, a serious wave-drag penalty is indicated.

Wings with spanwise variation of leading-edge contour.- Zero-lift drag data for wings of plan form B with full-span contour variation are given in figure 7. Data for both plane and conically cambered wings are shown. The bulbous-contour variation was effectively the same as that for which low-speed data were presented in figure 3.

At all Mach numbers, the data show only small differences in drag levels between corresponding bulbous and conventional wings, although the former had the generally higher levels. Of particular interest is the fact that, in contrast with the constant-contour wings, drag differences were no greater above than below the Mach number for a sonic leading edge.

Unfortunately, there appear to be no other high-speed data on thin swept wings with spanwise variation of bulbous leading-edge contour. In the absence of such data, a geometric comparison of the full-span contour variation just mentioned, with the more appropriate designs for which low-speed data have been presented, is made in the next section; from that comparison, a generalized conclusion is tentatively drawn.

Outboard Bulbous Contours: Implications of the Data

Compared in figure 8 are the distributions of leading-edge radius for all the variable-contour wings reviewed herein. Not only the radii, but the increases of radius over the conventional values are shown. From this comparison, from over-all contour considerations, and from foregoing drag data, the following qualitative conclusions are inferred:[1]

1. For the cut-contour wings, a more significant wave-drag penalty is likely than that indicated in figure 7 for the full-span variable-contour wings. The penalty should be far less, however, than that indicated in figure 6 for the constant-bulbous-contour wings. The question is open as to whether the penalty would be greater above, than below, sonic-leading-edge speed. Note that all these wings are of plan form B.

2. For the high-lift configuration (i.e., wing of plan form C, with flaps retracted) the part-span bulbous contour might well result in no wave-drag penalty, at least at Mach numbers up to about 2. This seems especially probable in view of the very short chordwise extent of the bulbous contour (fig. 4). Further, the considerable degree of taper in this wing should also tend to minimize any effect, since it places only a small portion of the total wing volume in the region of the bulbous contour.

These qualitative conclusions for specific designs lead to the following generalization: in a thin swept wing with appreciable taper, outboard concentration of a bulbous contour, sufficient in spanwise extent to give most or all of the low-speed benefit attainable from its use, may not result in any significant wave-drag penalty even at fairly high supersonic-leading-edge speeds.

[1]It is important to recognize that the geometric basis of these inferences is not leading-edge radius alone, but over-all bulbous geometry. While figure 8 affords a convenient graphic comparison, it should not be regarded as an adequate basis, of itself, for drawing the inferences. It is felt that the leading-edge radius is a relatively crude parameter, depending as it does on "the second derivative of the contour" and applying in the last analysis to one and only one point. However, for this report, the leading-edge radius is regarded as having semiquantitative significance beyond the leading edge itself, in view of the smooth continuity of curvature characterizing all contours.

Further research enabling a more definitive conclusion is needed. The separate effects of such variables as extent of bulbous contour, leading-edge sweep, taper ratio, and aspect ratio call for investigation.

Area-Rule Considerations and Data

The bulbous and conventional wings of plan form B for which transonic data were presented in figure 6 were also tested with the basic Sears-Haack body indented for the respective wings. The effect of these indentations on zero-lift drag is shown in figure 9, from which it can be seen that the drag reductions due to the indentations were far greater than the differences in drag between any two corresponding bulbous- and conventional-wing models. This is brought out further by the bar graph of figure 10, which is a comparison of experimental and theoretical drag-rise coefficients. Agreement between theory (ref. 11) and experiment is seen to be good.

It may be concluded that at speeds well below sonic-leading-edge speed, (1) area-rule adjustments appear to be equally effective for configurations with wings of either bulbous or conventional leading-edge contour; and (2) wave drag can be calculated with equal accuracy for both cases.[2]

There are no data on the effectiveness of area-distribution adjustments for wings with sonic or supersonic leading edges of bulbous contour. Some effectiveness would certainly be expected, but the question of how much awaits the results of future research. However, the generally good reliability with which wave drag has been calculated for a limited number of unindented-body configurations with rounded, sonic or supersonic leading edges (refs. 12 and 13) suggests that the effect of area-rule adjustments should be calculable with at least semiquantitative accuracy. Of interest among the computations that have been made are the only ones known for a bulbous wing, namely the slightly cambered wing of plan form B (ref. 12). At a Mach number of 1.5, just above sonic-leading-edge speed, agreement with experiment was excellent. At the only higher Mach number for which the computation was performed, 1.9, agreement with experiment was poor. Unfortunately, the interpretation of these isolated results is complicated by at least three factors: (1) the limitations of the computational method, and of its theoretical basis, as applied to rounded supersonic leading edges (discussed in both the references cited); (2) the presence of camber in the bulbous wing (discussed in ref. 12); and (3) the possibility that the experimental data at $M = 1.9$ may be less reliable than at $M = 1.5$ (discussed in ref. 13).

[2]As suggested in reference 3, it should be possible to make area-distribution adjustments on the wing itself aft of maximum thickness without detriment to the low-speed characteristics.

Despite the limited nature of the high-speed data reviewed, the general conclusion is suggested that a combination of appropriate spanwise variation of leading-edge contour with favorable-interference design might not yield any wave-drag penalty due to bulbousness, at least at the design speed.

CONCLUSIONS

Important aspects of current data on thin swept wings with bulbous leading-edge contours (i.e., with relatively large leading-edge radii and smooth continuity of curvature on the upper surfaces) have been reviewed. The following conclusions are indicated:

1. Within the limitations of given thickness ratio and camber, the bulbous type of leading-edge contour affords a powerful geometric means of maintaining attached flow around the leading edge of a thin swept wing at low speeds.

2. For many applications, outboard concentration of a bulbous contour will yield most or all of the low-speed benefit attainable from the use of such a contour.

3. Wave drag at zero lift does not appear to be sensitive to leading-edge contour at speeds well below sonic-leading-edge speed.

4. At higher speeds, a full-span, constant, bulbous contour is likely to result in a serious wave-drag penalty.

5. Outboard concentration of a bulbous contour, in a wing with appreciable taper, may not result in any significant wave-drag penalty. Further research on the separate effects of such variables as extent of bulbous contour, leading-edge sweep, taper ratio, and aspect ratio, is required to establish a more definitive conclusion.

6. Area-rule adjustments, for design Mach numbers well below that for a sonic leading edge, appear to be equally effective for either bulbous or conventional leading-edge contours. Wave-drag calculations for these Mach numbers appear to be equally reliable.

7. The generally good reliability with which wave drag has been calculated for a limited number of unindented-body configurations with rounded sonic or supersonic leading edges suggests that the effect of area-rule adjustments for such leading edges of bulbous contour should be calculable with at least semiquantitative accuracy.

8. Despite the limited nature of the high-speed data reviewed, it is suggested that a combination of appropriate spanwise variation of leading-edge contour with favorable-interference design might not yield any wave-drag penalty due to bulbousness, at least at the design speed.

Ames Aeronautical Laboratory
National Advisory Committee for Aeronautics
Moffett Field, Calif., Feb. 11, 1957

APPENDIX

PREVIOUSLY UNPUBLISHED DATA FOR THE WING OF PLAN FORM B

Presented in figure 11 are the low-speed longitudinal characteristics of the wing of plan form B with the inboard contours that have been designated "cuts 1" and "2." In figure 12, the effect of split flaps is shown. These data may be considered as supplementing the data of reference 4, to which the reader is directed for details of the model and test conditions.

Contour Details

The outboard contour was designated "modification 4" in reference 4. The inboard contour for each cut was obtained by using straight-line elements along constant-percent-chord lines from the outboard extremity of the cut to an imaginary NACA 64A006 section so placed in the extended wing panel as to result in the desired value of leading-edge radius at the wing-body juncture. The outboard extremities of the cuts, at the leading edge, were at 55- and 60-percent semispan, respectively. The spanwise variations of leading-edge radius, and representative section contours, have already been presented in figure 2.

The sharp leading-edge fairing at the body juncture, tested in conjunction with cut 1, consisted of sheet metal wrapped around wooden ribs on the leading edge. It was sharp only at the body juncture itself, and increased in roundness as it progressed outboard, finally fairing into the wing at the 20-percent-semispan station (approximately 5-percent semispan from the body).

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12. Holdaway, George H.: Additional Comparisons Between Computed and Measured Transonic Drag-Rise Coefficients at Zero Lift for Wing-Body-Tail Configurations. NACA RM A55F06, 1955.

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TABLE I.- SUMMARY OF MATERIAL REVIEWED

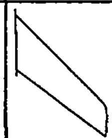
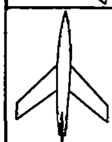
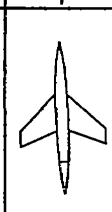
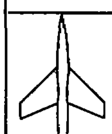
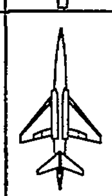
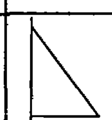
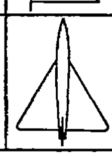
Plan-form designation	Model sketches	Leading-edge contour vs. span	Figure	Data presented	M	$R \times 10^{-6}$	Sources
A		Constant	1	Low-speed polars	<0.2	9	Ref. 1
		Constant	6	$C_{D(o)}$, $\Delta C_{D(o)}$ vs. M	0.8-2.1	3-13	Ref. 2
B		Constant	1	Low-speed polars	0.13	10	Refs. 3,4
		Variable	2	Low-speed polars	0.13	10	Appendix and ref. 4
		Variable	3	Low-speed polars	0.13	10	Appendix and ref. 4
		Constant	6	C_{D_o}, ΔC_{D_o} vs. M	0.6-1.9	2.9,6.9	Refs. 3,5
		Variable	7	C_{D_o} vs. M	0.6-0.9, 1.2-1.9	2.9	Ref. 6
		Constant	9	C_{D_o} vs. M	0.8-1.2	6.9	Ref. 5
		Constant	10	ΔC_{D_o}: theory vs. experiment	1.05, 1.20	6.9	Ref. 5
C		Variable	4	Low-speed drag and pitching moment	0.11	10	Table II and Ref. 7
		Variable	5	$C_{L_{max}}$ vs. extent of bulbous contour	0.11	10	Table II
D		Constant	6	C_{D_o} vs. M	0.6-1.1	2.2-2.8	Ref. 8
E		"Constant" (see p. 5)	6	$C_{D(o)}$ vs. M	0.8-1.95	7-29	Ref. 9

TABLE II.- DATA FOR THE WING OF PLAN FORM C

[For details of the model and wind-tunnel test conditions, see reference 7. Area-suction flow quantities were well above critical. Dihedral of the horizontal tail was -15°.]

(a) Coordinates of the bulbous contour, in percent of the chord normal to the leading edge[1]

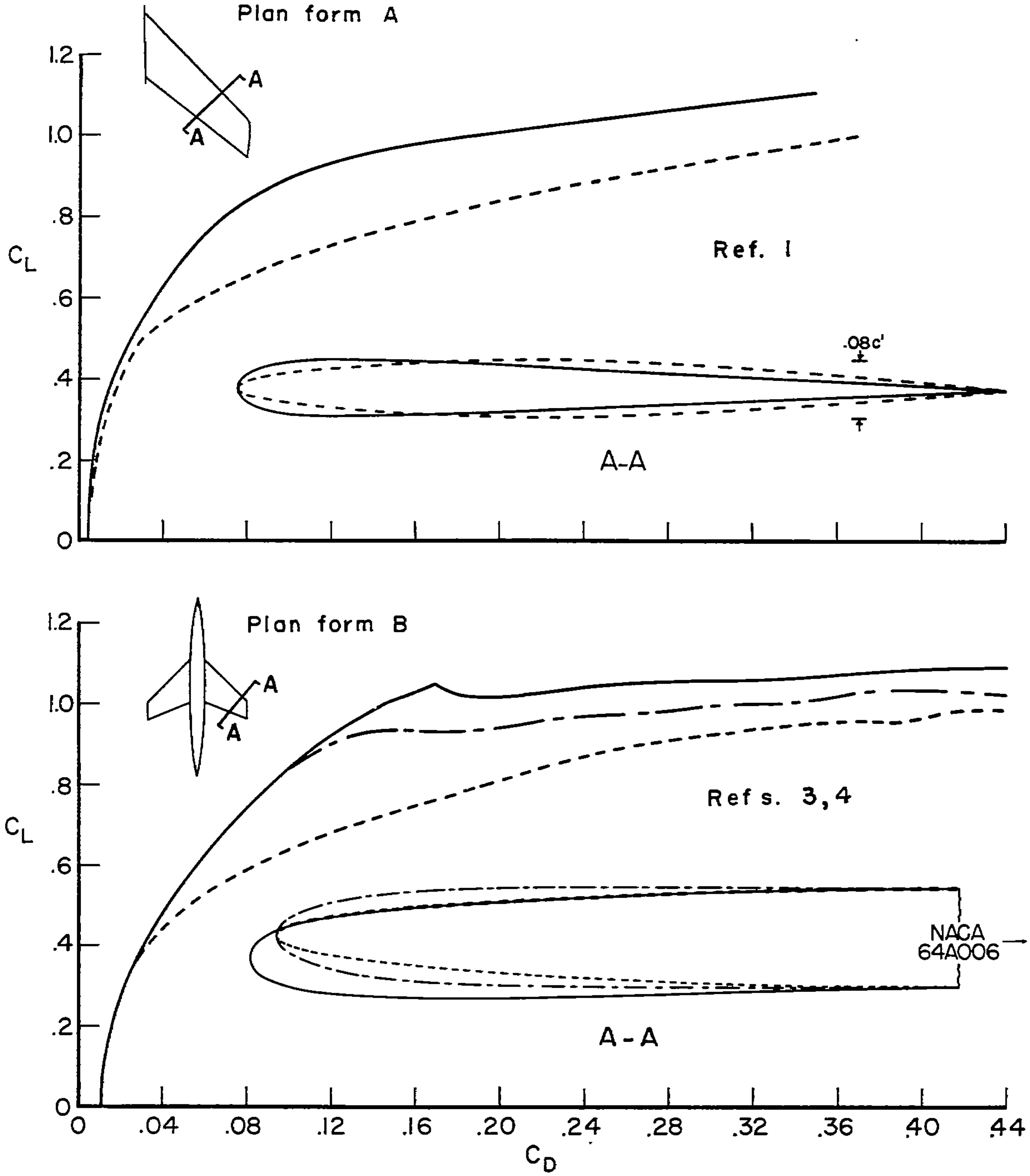
Station	Ordinates		Station	Ordinates	
	Upper surface	Lower surface		Upper surface	Lower surface
0	-0.61	-0.61	2.05	1.08	-1.75
.05	-.30	-.91	2.55	1.23	-1.75
.10	-.18	-1.03	3.06	1.35	-1.74
.26	.07	-1.25	3.57	1.45	-1.71
.51	.35	-1.46	4.09	1.52	-1.70
.77	.54	-1.57	4.60	1.60	-1.69
1.28	.82	-1.69	5.10	1.67	-1.67
Leading-edge radius: 0.90					

[1]The contour was similar to the smaller "modified leading edge" of reference 7, but was more carefully contoured from wood, rather than consisting of sheet metal wrapped around wooden ribs. Coordinates are given normal to the leading edge, rather than as illustrated herein, to be consistent with the presentation in reference 7.

TABLE II.- DATA FOR THE WING OF PLAN FORM C - Concluded

(b) Longitudinal data

Outboard extent of bulbous contour: 0				Outboard extent of bulbous contour: 0.3 b/2			
α, deg	C_L	C_D	C_m	α, deg	C_L	C_D	C_m
4.63	0.803	0.211	-0.104	4.63	0.801	0.210	-0.105
8.79	1.014	.250	-.136	8.79	1.012	.250	-.138
12.93	1.203	.296	-.164	12.93	1.206	.297	-.171
15.00	1.301	.325	-.181	15.00	1.298	.326	-.181
17.03	1.345	.371	-.172	17.07	1.397	.358	-.197
19.00	1.294	.430	-.119	19.15	1.497	.399	-.206
19.99	1.284	.450	-.109	20.17	1.527	.417	-.204
20.98	1.269	.480	-.118	21.18	1.547	.445	-.183
23.00	1.295	.562	-.130	23.07	1.396	.532	-.145
25.03	1.343	.636	-.133	25.10	1.430	.632	-.151
27.06	1.379	.736	-.184	27.08	1.405	.728	-.183
Outboard extent of bulbous contour: 0.4 b/2				Outboard extent of bulbous contour: 0.6 b/2			
4.63	.804	.212	-.103	4.64	.812	.212	-.098
8.78	1.004	.250	-.134	8.78	1.004	.249	-.135
12.92	1.196	.297	-.163	12.93	1.205	.294	-.161
15.00	1.305	.327	-.180	15.00	1.301	.324	-.175
17.15	1.396	.363	-.196	17.07	1.400	.358	-.196
19.16	1.512	.402	-.218	19.16	1.508	.401	-.209
21.23	1.607	.448	-.222	21.23	1.615	.450	-.224
22.25	1.637	.478	-.222	22.26	1.645	.481	-.227
23.25	1.632	.514	-.195	23.22	1.602	.512	-.205
24.24	1.618	.546	-.190	24.20	1.565	.551	-.169
25.17	1.535	.601	-.166	25.18	1.535	.607	-.157
27.10	1.441	.711	-.168	26.15	1.506	.715	-.201
29.12	1.461	.826	-.177	29.17	1.524	.794	-.202
Outboard extent of bulbous contour: 0.79 b/2 (exposed wing span)							
4.64	.814	.214	-.100	22.27	1.656	.475	-.233
8.79	1.018	.250	-.137	23.25	1.641	.507	-.214
12.93	1.206	.297	-.168	24.24	1.615	.525	-.198
15.00	1.305	.324	-.182	25.15	1.505	.590	-.168
17.08	1.402	.357	-.197	27.13	1.474	.682	-.196
19.15	1.504	.398	-.215	29.14	1.492	.758	-.201
21.24	1.618	.447	-.230				



'igure 1.- Typical effect of bulbous leading-edge contours at low speeds.

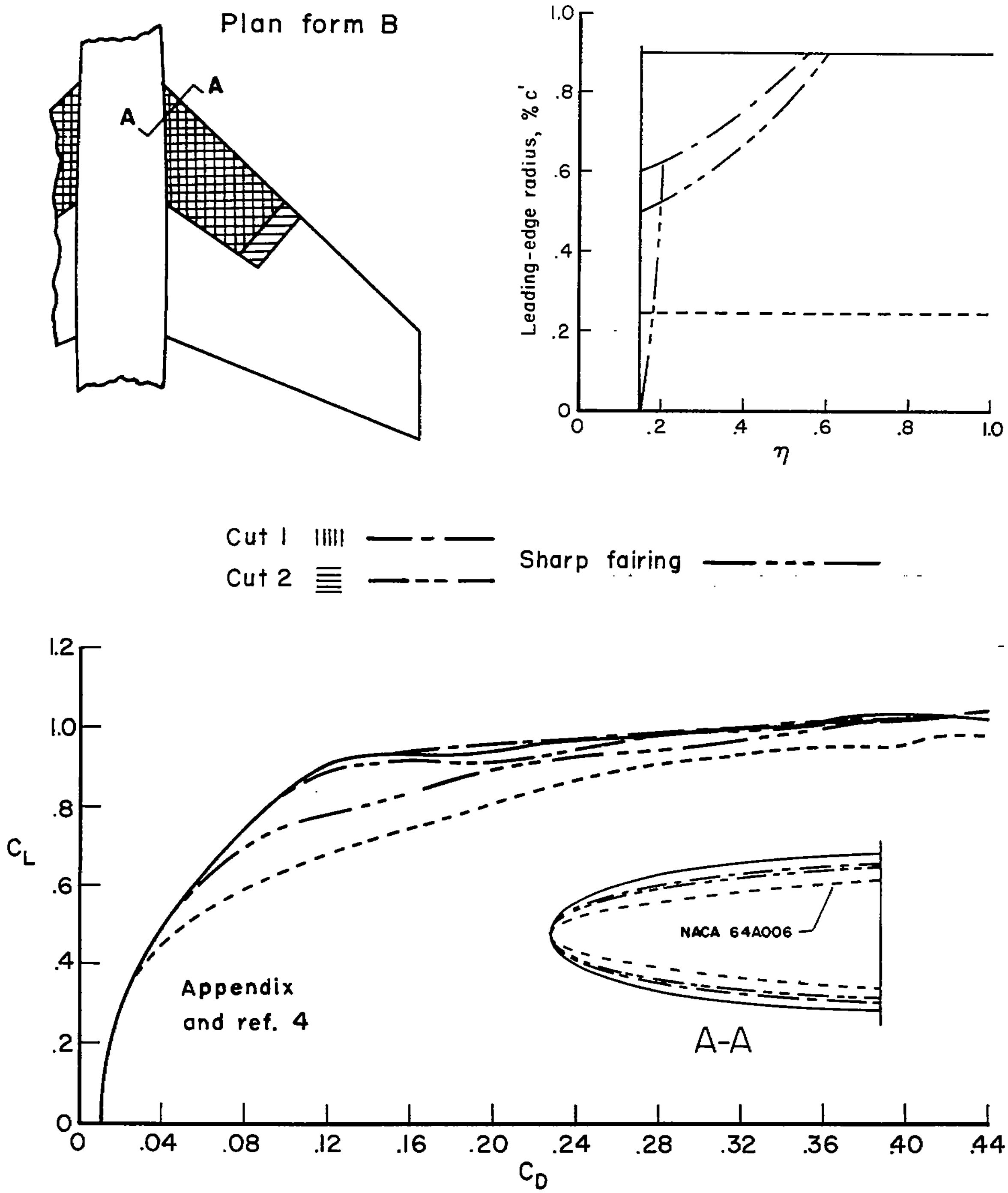


Figure 2.- Effect at low speed of progressively thinning the inboard forward region of a bulbous-contoured wing.

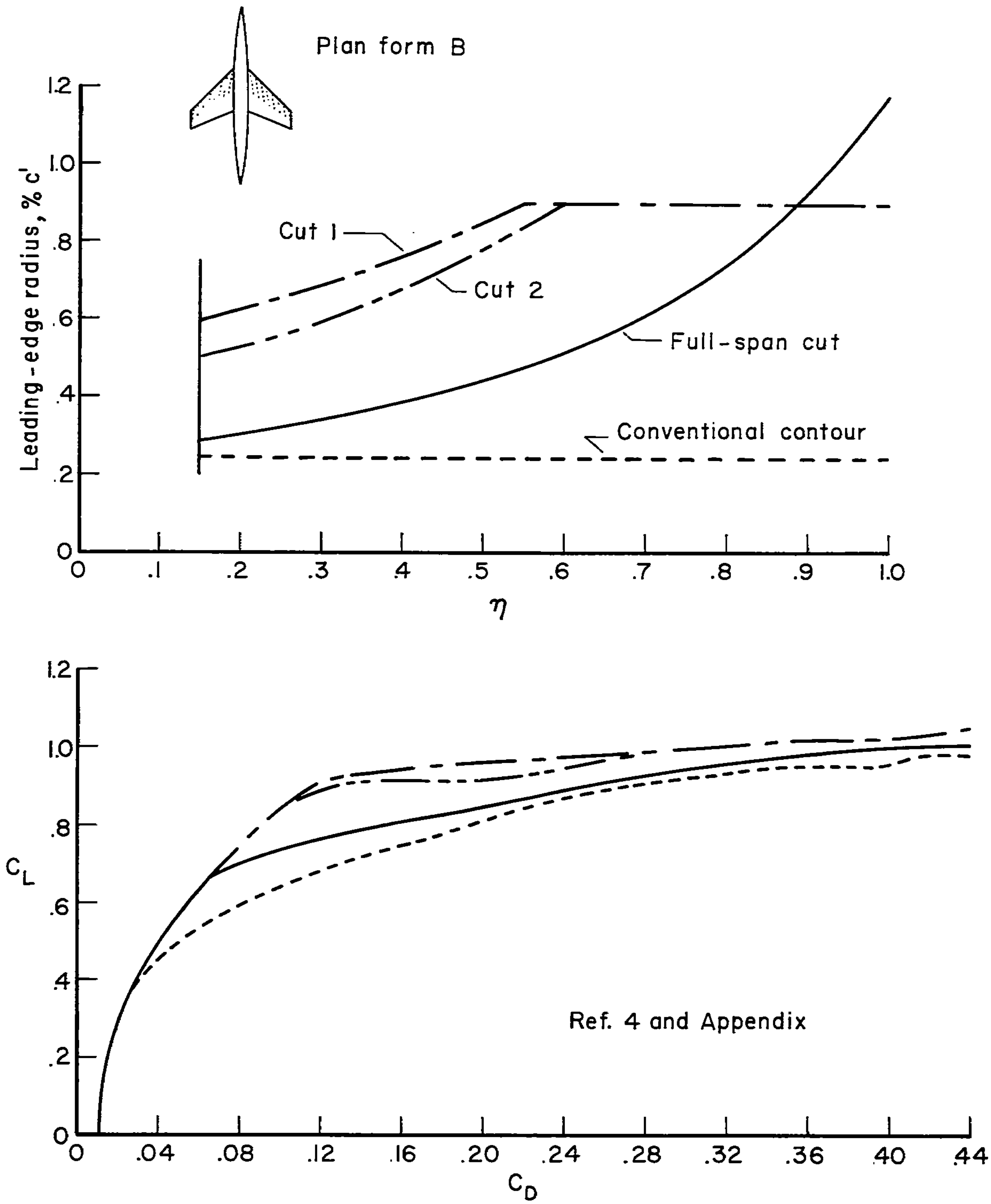


Figure 3.- Comparative effect at low speed of three spanwise variations of leading-edge contour.

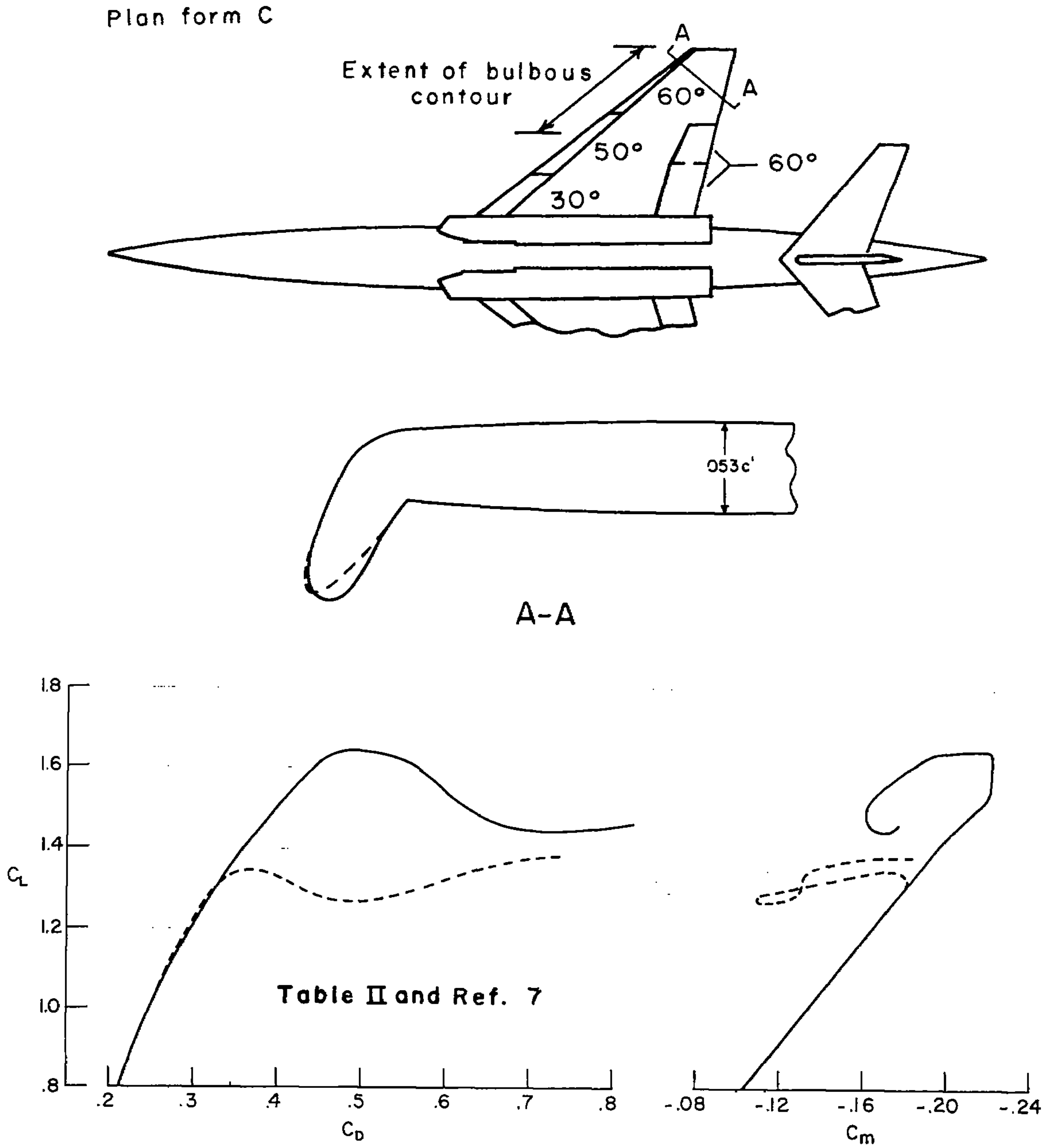


Figure 4.- Effect of a part-span bulbous leading edge on the low-speed characteristics of a high-lift configuration with area-suction boundary-layer control.

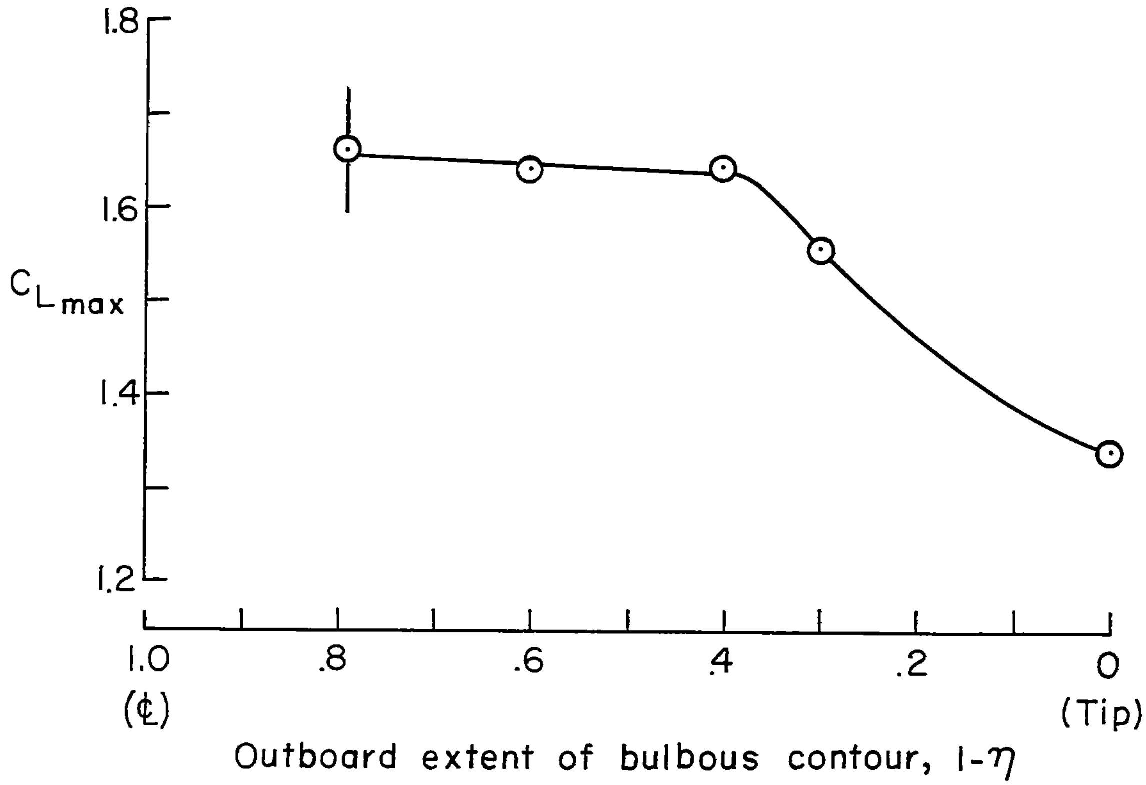


Figure 5.- Effect of the outboard extent of the bulbous contour of figure 4 on the maximum lift of the configuration.

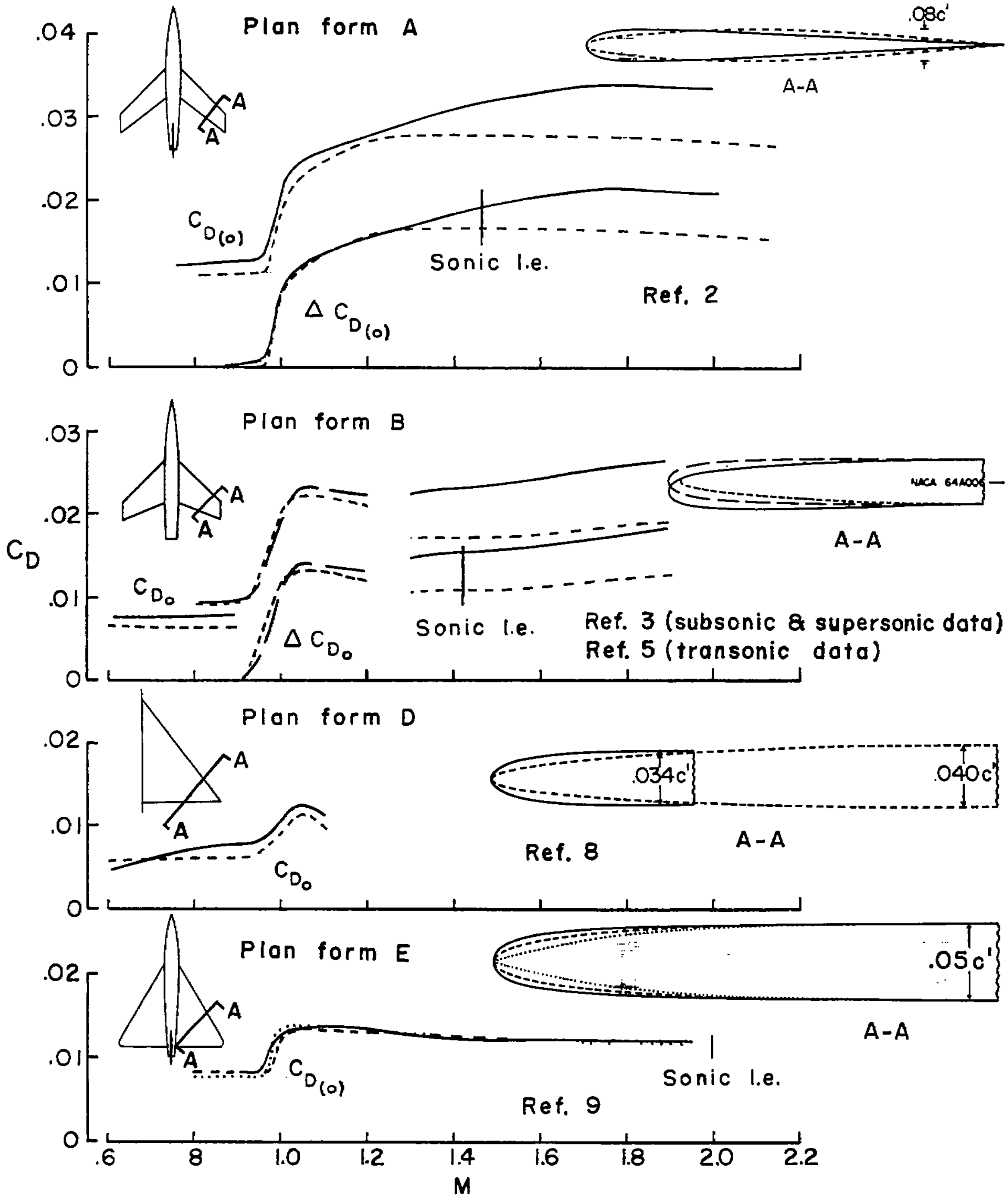


Figure 6.- Effect of constant bulbous leading edges on drag and drag rise near zero lift.

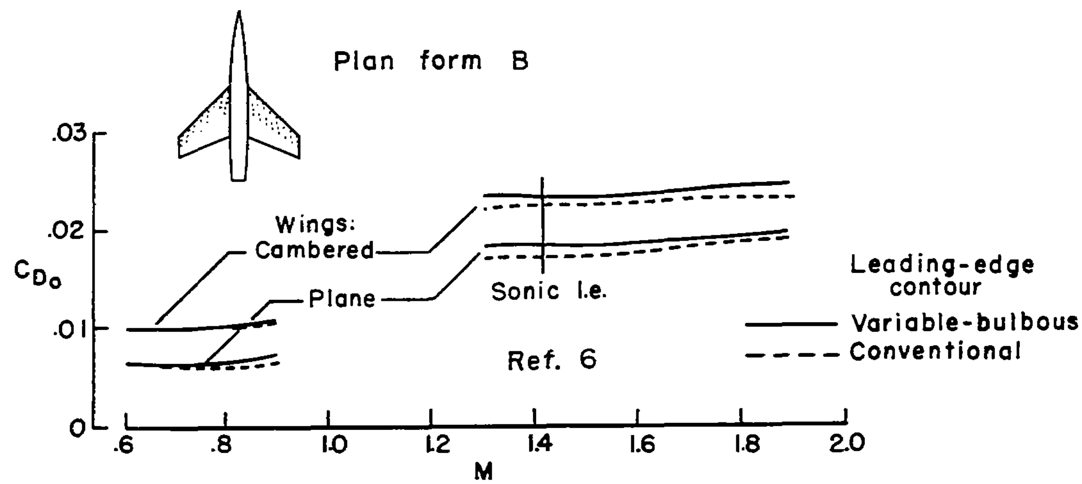


Figure 7.- Effect of full-span variation of leading-edge contour on drag at zero lift.

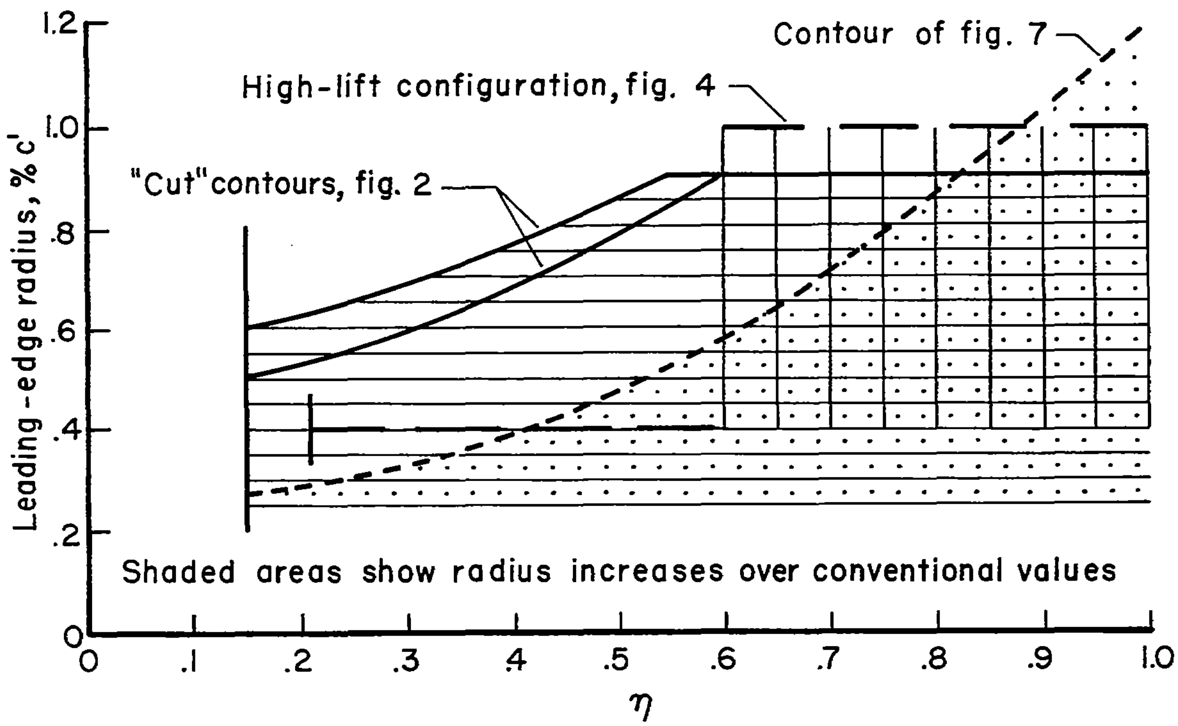


Figure 8.- Comparison of the distributions of leading-edge radius for the variable-contour wings.

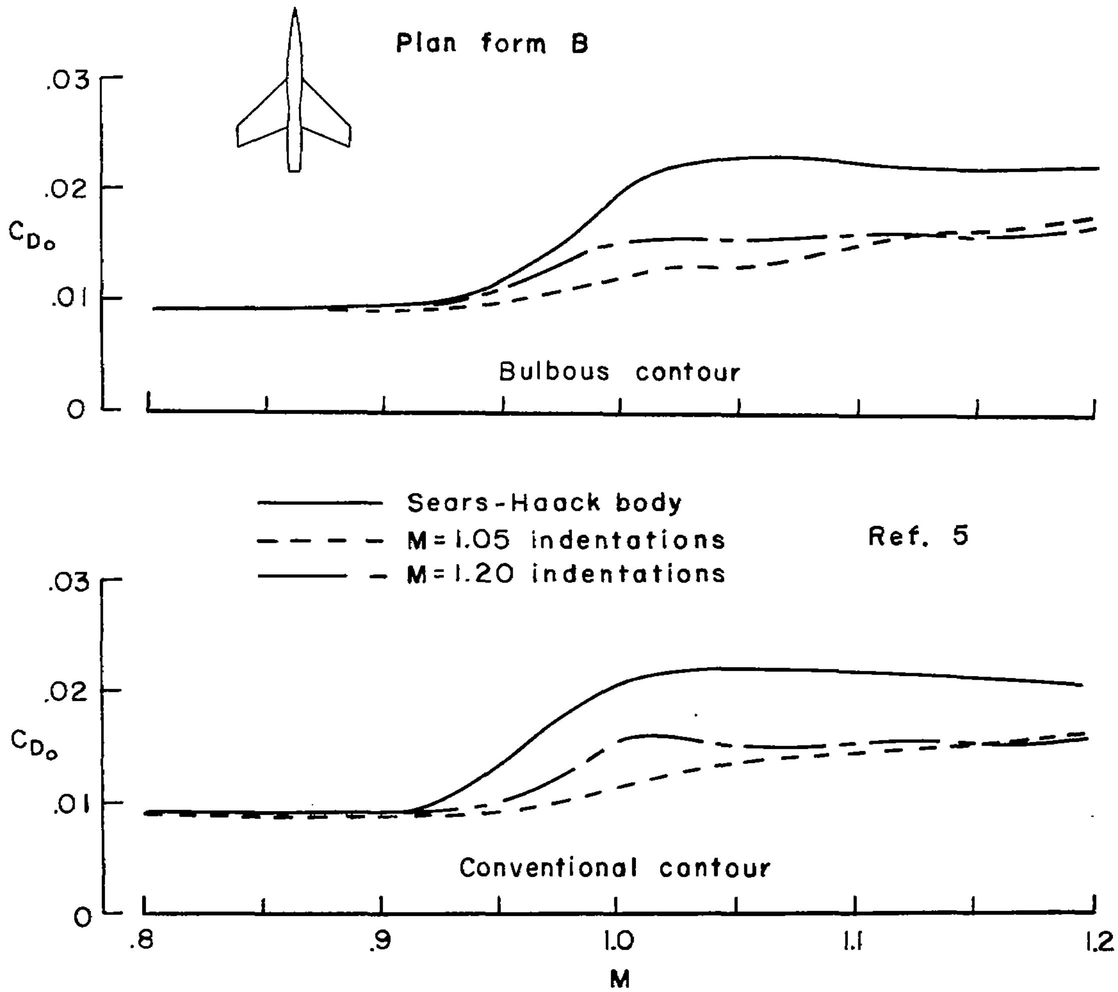


Figure 9.- Effect of body indentations on drag at zero lift for bulbous and conventional wings.

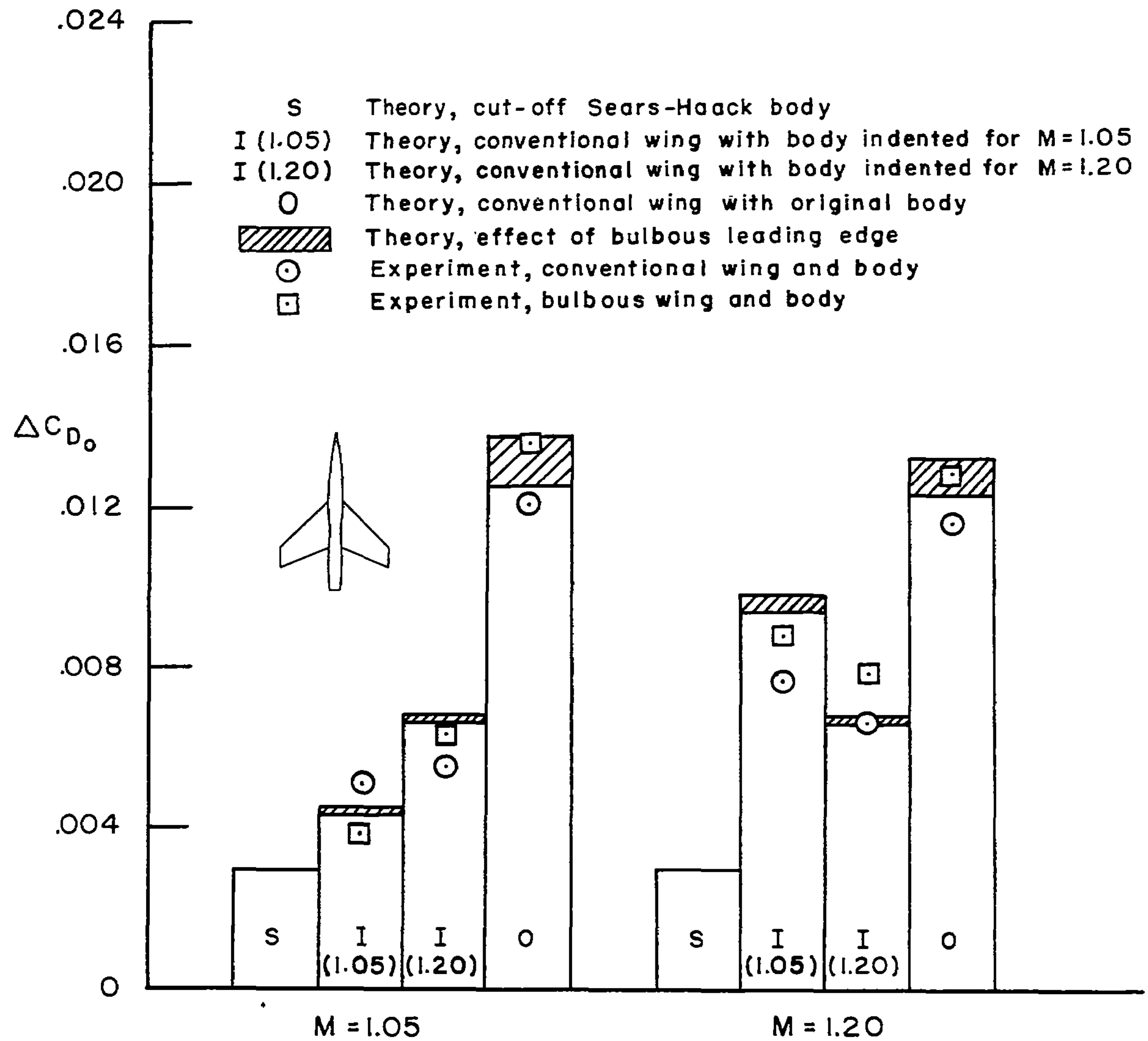
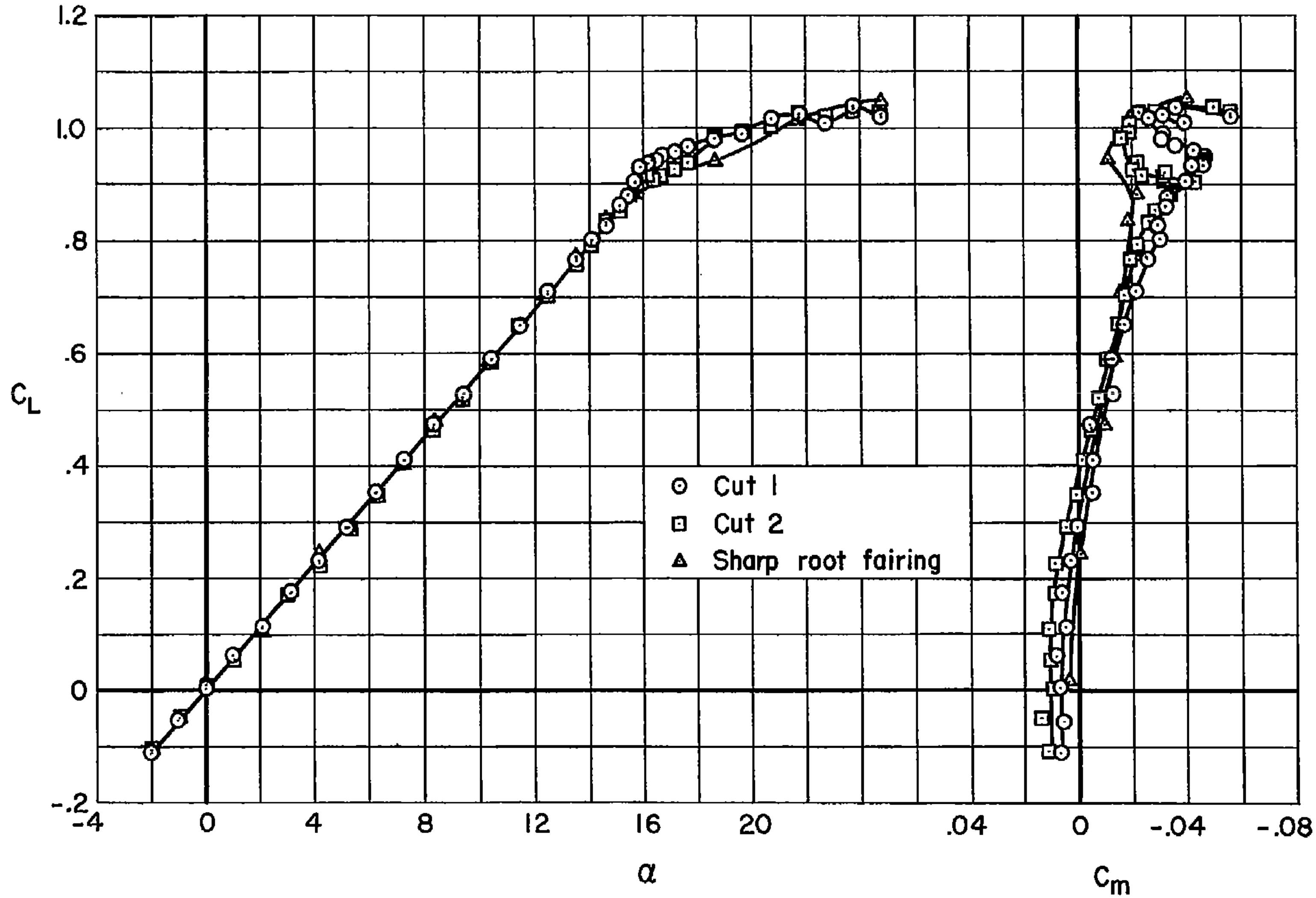
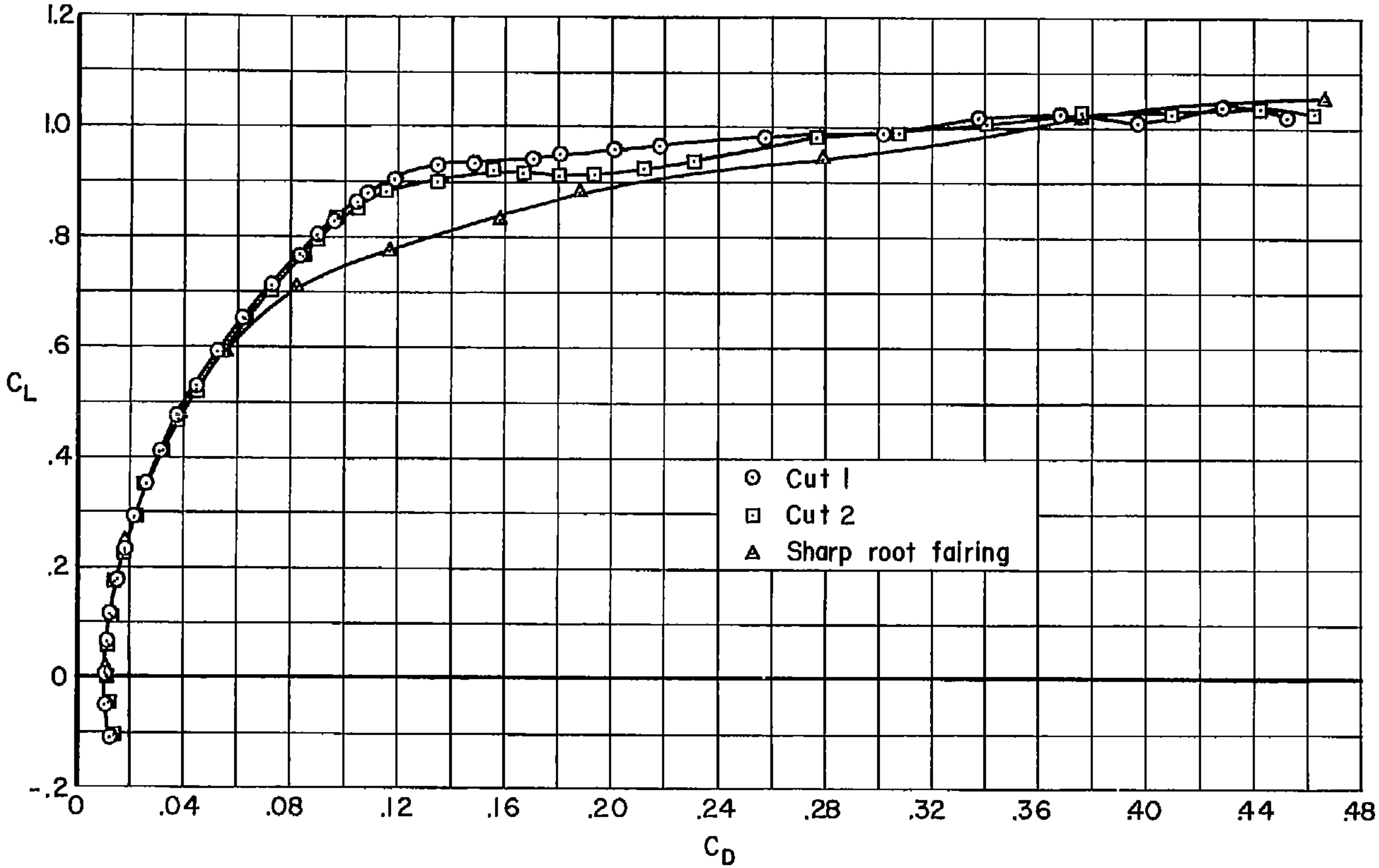


Figure 10.- Comparison of theoretical and experimental zero-lift drag-rise coefficients for the configurations of figure 9.



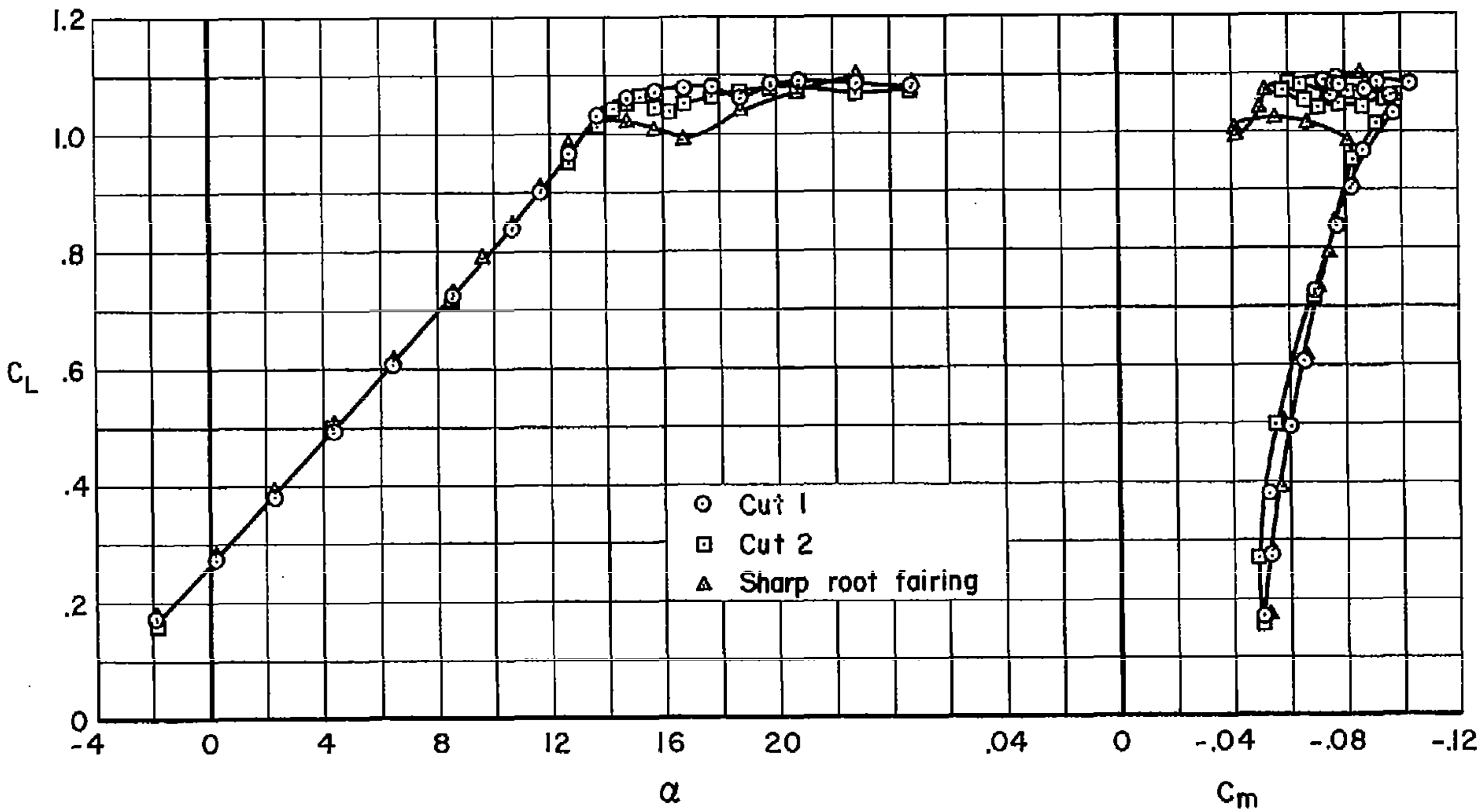
(a) C_L vs. α, C_m

Figure 11.- Low-speed longitudinal characteristics of the wing of plan form B with "cut" contours inboard.



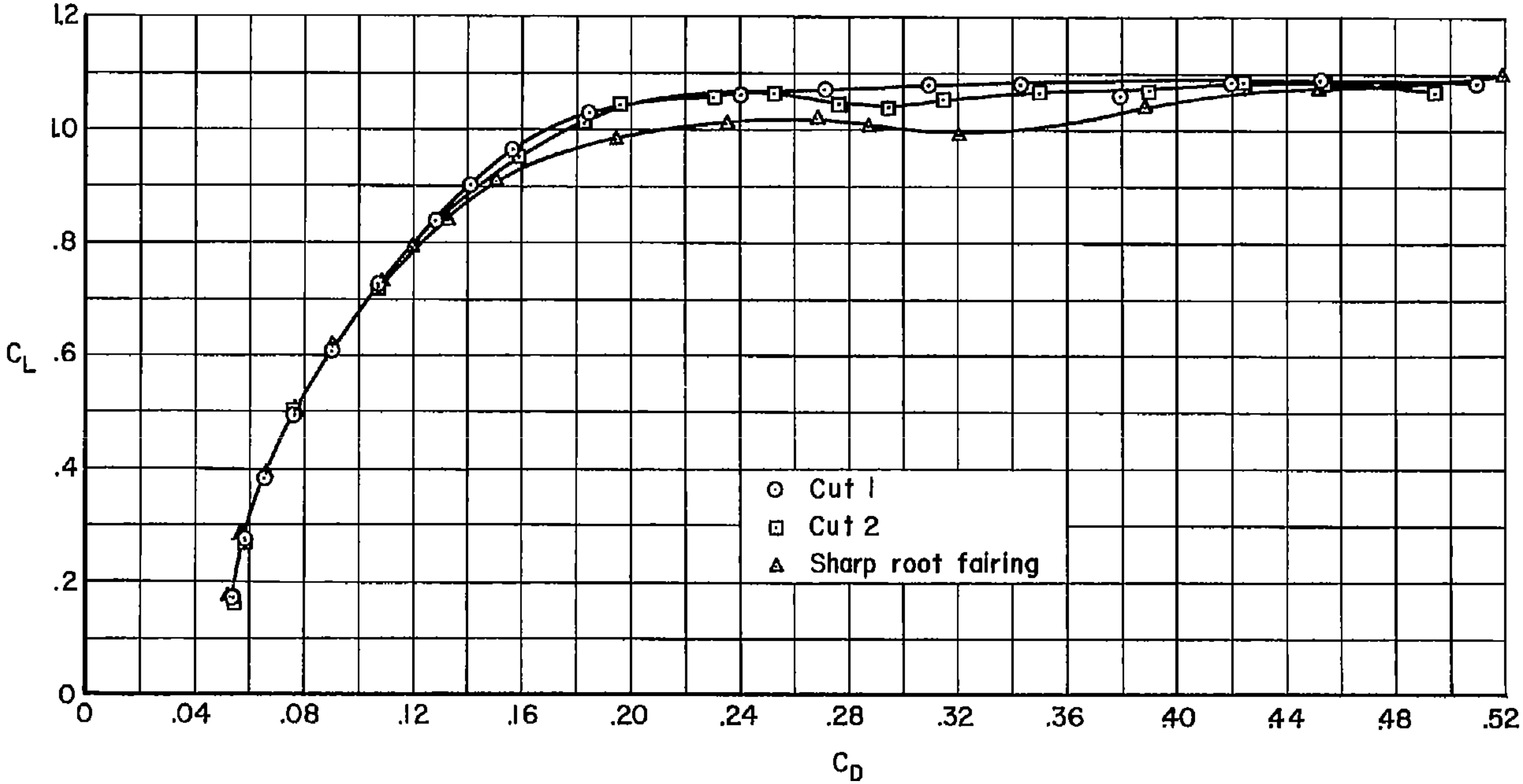
(b) C_L vs. C_D

Figure 11.- Concluded.



(a) C_L vs. α, C_m

Figure 12.- Effect of split flaps of span 0.55 b/2, deflected 37°, on the logitudinal characteristics of the wing with "cut" contours.



(b) C_L vs. C_D

Figure 12.- Concluded.